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**APPLICATIONS OF EXPERT SYSTEMS
IN ENVIRONMENTAL ENGINEERING**

by

Lewis A. Rossman
Water and Hazardous Waste Treatment Research Division
Risk Reduction Engineering Laboratory
Cincinnati, Ohio 45268

RISK REDUCTION ENGINEERING LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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APPLICATIONS OF EXPERT SYSTEMS IN ENVIRONMENTAL ENGINEERING

Lewis A. Rossman
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

1. Abstract

Expert systems are a promising computer-based approach to helping environmental engineers solve difficult problems. A number of such systems have been developed to date in the areas of hazard assessment, modeling support, process failure diagnosis, and regulatory support. The US Environmental Protection Agency has several programs underway to introduce this technology into its operations. The most ambitious of these is the work being undertaken by EPA's Hazardous Waste Engineering Research Laboratory. They are developing five systems that support the review of applications for operating permits for RCRA hazardous waste facilities and selection of remedial action alternatives at Superfund cleanup sites. The most highly developed of these is FLEX, a program that evaluates the chemical resistance of synthetic liners exposed to wastes contained in landfills and impoundments. FLEX contains 347 rules encoded in the Prolog language along with special data management routines written in C. Work on FLEX and other systems has identified a number of issues important to successful implementation of expert systems within an organization such as EPA. More successful applications of the technology to real engineering problems are needed to maintain the momentum achieved to date.

2. Introduction

Expert systems are computer programs that encode the knowledge and reasoning used by specialists to solve difficult problems in narrowly defined domains. They rely more on heuristic methods, rules of thumb, and pattern matching to achieve their results, rather than numerical models and algorithms. Problems involving classification, interpretation, diagnosis, prediction, instruction, planning, and design are all amenable to expert system solutions.

Environmental engineering readily lends itself to applications of expert systems. It is a multi-disciplinary area whose problems can require specialized expertise in such diverse fields as chemistry, biology, fluid mechanics, mathematics, statistics, economics, and law. Individual environmental engineers will not always be well versed in all of these areas. Expert systems can assist in providing solution-directed knowledge in unfamiliar subjects.

Environmental engineering is also highly dependent on empiricism. The complex chemical and biological behavior of

environmental systems is not always capable of being described through formal mechanistic models. A greater reliance on experience and intuition is required in many cases. Very often the problem solving techniques of successful practitioners cannot be easily taught through textbooks or manuals. Expert systems can help transfer these techniques to less experienced personnel.

Expert systems can also assist the environmental engineer in dealing with uncertain, incomplete, and qualitative data. Traditional algorithmic solution methods are not well equipped to handle these kinds of data. In addition, environmental engineers often work within a framework shaped by numerous government rules and regulations. The rule-based nature of such regulations make them readily compatible with the rule-based representation of knowledge used in many expert systems. Thus these systems can help engineers reconcile complicated regulatory requirements and help environmental control agencies insure that their regulations are complied with.

This chapter provides a general review of how expert systems are being applied to environmental engineering problems today. It gives more detailed treatment to how one particular organization, the US Environmental Protection Agency (EPA), has been trying to introduce this technology into its operations. Special emphasis is given to EPA's activities in the area of hazardous waste management and the factors that are influencing the successful implementation of this new technology.

3. Review of Applications

Applications of expert systems to date in environmental engineering can be conveniently categorized with respect to the following general types of activities: hazard assessment, modeling support, process failure diagnosis, and regulatory support. A brief review of the documented systems within each category follows. More detailed reviews have been written by Rossman and Siller (1987) and Hushon (1987).

Hazard Assessment. This type of activity usually involves interpreting site conditions to estimate the extent of potential environmental or public health hazards. It can require the ability to access both textbook-type and experiential knowledge from a variety of disciplines in a timely manner. Three different expert systems have been developed to assess the hazard potential of sites contaminated with hazardous wastes (the RPI Site Assessment System (Law et al., 1986), GEOTOX (Mikroudis, et al., 1986), and DEMOTOX (Ludvigsen, et al., 1986)). Another system, FRES, assists local firemen and police in responding to emergency chemical spills (Hushon, 1986).

Modeling Support. Expert systems in this area provide intelligent front-ends and output interpreters to existing numerical modeling

programs. The QUAL2E Advisor suggests appropriate values for the input parameters to the popular QUAL2E water quality simulation model (Barnwell et al., 1986). CORMIX1 is a system that helps select the most appropriate type of numerical model to use in calculating the zone of initial dilution for waste discharges into receiving waters (Doneker and Jirka, 1988). The HAWAMAX system (Shih and Bernard, 1988) provides an expert interface to a quantitative risk analysis model of hazardous waste site cleanups. Knight (1987) describes a system that selects and estimates the costs of process units suitable for upgrading small water supplies.

Process Failure Diagnosis. This category of applications helps identify the causes and remedies for malfunctions in pollution control facilities. These types of problems can utilize large amounts of empirical and heuristic knowledge that is not readily available in textbooks or manuals. Diagnostic systems have been developed for incinerators (Huang, et al., 1986), activated sludge wastewater treatment systems (Johnston, 1985), and anaerobic digesters (Barnett and Andrews, 1987). Another expert system for diagnosing activated sludge problems is described by Patry in this volume.

Regulatory Support. The principal function of systems in this area is to carry out some regulatory task in an environmental control agency that involves a significant technical content (e.g., document preparation or regulatory review). One such system, the Work Assignment/Work Plan Memo Generator, prepares a document that outlines the tasks and the resource requirements needed to investigate and plan cleanup activities at abandoned hazardous waste sites under EPA's Superfund program (Paquette, 1986). SEPIC is an expert system that assists the Austin-Travis County Health Department in issuing permits for on-site private sewage disposal (Hadden and Hadden, 1985). The US EPA is also developing a number of expert systems to assist in its regulatory activities. These will be discussed in the next section.

4. EPA Programs

The US EPA is responsible for administering a number of pieces of environmental legislation concerned with limiting the adverse impacts of pollutants and hazardous materials released to the land, air, and water. Table 1 lists several of these acts along with their most significant regulatory provisions. The Agency is organized into a Headquarters Office in Washington, DC, ten Regional Offices throughout the US, and a number of research laboratories and other support facilities also scattered across the country. Rules, regulations, policy and guidelines for implementing the laws listed in Table 1 are usually promulgated by several separate media-specific offices in EPA's Headquarters (e.g., Office of Air, Office of Water, Office of Pesticides and Toxic Substances, etc.). Research and technical support for this process is provided by the research laboratories. The Regional

Offices actually administer the laws to the regulated community or provide oversight to the regulatory activities of State and local governments.

Since about 1984 there has been a growing interest within EPA in applying expert system technology to their regulatory activities. The major benefits of their use within the Agency are their ability to:

- * expedite the regulatory process and increases staff productivity,
- * document the rationale behind regulatory decision making thereby making it appear less obscure and arbitrary,
- * transfer lessons learned to others and provide training to new personnel,
- * allow site specific factors to be taken into account rather than worst case conditions, resulting in more equitable and cost-efficient regulation,
- * allow for consistent application of the Agency's rules and guidelines throughout all regions of the country.

Table 2 lists several expert system projects that have been initiated within EPA over the past few years. Most of these systems are either experimental prototypes or are continuing to receive additional development and testing prior to being introduced into the field. There is no central office within the Agency responsible for developing these systems. Instead, individual offices, or research labs in support of an office, pursue projects relevant to their specific regulatory mandates.

The Agency has also sponsored a number of other supporting activities. These include training programs given by outside instructors, internal workshops where developers and users can exchange ideas with one another, and an electronic bulletin board that allows individuals to pursue an on-going exchange of information. In addition, the EPA's Office of Information Resources Management is developing guidelines on the creation and use of expert systems within the Agency that will hopefully make the process more productive and less chaotic.

5. HWERL's Activities

The most ambitious program in expert systems within EPA is being undertaken by the Hazardous Waste Engineering Research Laboratory (HWERL) in Cincinnati, Ohio. This lab is developing systems to support the Agency's activities in the areas of hazardous waste management under the RCRA and CERCLA statutes. The RCRA activities involve assistance in reviewing permits for operating or closing land disposal facilities. The applications

for these permits contain technical information on such things as site location and geology, soil and synthetic liner design, leachate collection systems, runoff/runoff control, waste analysis and handling procedures, and closure cost estimates and financial assurances. Knowledgeable, consistent, and timely review of this information can require specialized training and field experience in a number of technical disciplines -- a situation that too seldom exists among the reviewers at EPA regional and state offices.

Table 2 lists four systems (FLEX, DIKE, WAPRA, and EXP-CES) that HWERL is developing to assist in this review process. FLEX evaluates the suitability of synthetic liner materials for landfills and surface impoundments; WAPRA checks for potential hazards that may occur when a facility proposes to handle mixtures of various chemicals; DIKE performs a simple geotechnical safety analysis on the design of surface impoundments; EXP-CES checks that a proposed closure plan for a landfill will maintain suitable isolation of the buried waste material.

HWERL's expert system activities supporting CERCLA, or the Superfund program, have centered on the process of selecting the best mix of clean-up technologies to apply to a specific abandoned hazardous waste site. This is a difficult, multi-dimensional decision problem involving questions of technical feasibility, economics, and risk evaluation. The technologies themselves come from a wide variety of engineering disciplines (e.g., geotechnical, chemical, wastewater, or mechanical engineering) thus requiring a broad base of knowledge to properly evaluate their suitability. A test prototype expert system, TECHSCRN, was developed from literature sources to evaluate the technical feasibility of individual containment and removal actions. Future plans call for expanding the system to include: i) waste treatment/destruction processes, ii) grouping of individual processes into unit systems, and iii) cost estimating capabilities.

6. Review of FLEX

In order to convey what is involved in constructing an operational expert system, this section describes HWERL's efforts in developing their first system, FLEX. FLEX (Flexible Liner Evaluation Expert) evaluates the chemical resistance of synthetic polymeric liner materials against the wastes they are to contain in landfills and surface impoundments. Chemical resistance is usually established through immersion testing -- pieces of the liner are immersed in the waste to be contained and changes in liner chemical and physical properties are monitored over a several month period. Test results must be submitted as part of the application to receive an operating permit for a hazardous waste facility.

Usually immersion tests offer only indirect evidence of a liner's effectiveness. Very often the results must be subjectively interpreted by liner material specialists. Such specialists are in short supply and are not readily available to permit reviewers at EPA and state offices. The FLEX system was developed to overcome this problem. In addition to helping expedite the review process, FLEX was intended to provide more consistent decision making among regions and to codify the Agency's rationale in evaluating liner designs.

Work on FLEX began in 1984 with a small demonstration project exploring the feasibility of knowledge acquisition from one expert for one material, polyvinyl chloride (PVC). Since that time two more general classes of liner materials have been added (high density polyethylene (HDPE) and chlorosulphonated polyethylene (CSPE)), five additional experts have been consulted, three generations of software implementations have been developed, and a system verification study has been conducted, all at a total cost in excess of \$200,000. These developments are summarized in Table 3. At this time the system is being distributed to EPA regional offices for final testing and review by the user community prior to its general release.

The knowledge contained in FLEX is structured in terms of the logic flow diagram shown in Figure 1. Evidence for the top level conclusion, that the liner is not resistant, comes from indications of one or more failure modes that the liner may experience. A specific failure mode is inferred from patterns in the immersion test data. These patterns involve combinations of changes and trends in liner properties over time. If no evidence is found to support any of the failure modes, then the liner is deemed acceptable.

This conceptual framework has been implemented in a micro-computer-based system written in both Prolog and C. The system's knowledge base consists of production rules that are encoded in the Prolog language. These rules are IF-THEN statements that relate immersion test results to test patterns, and test patterns to failure modes. Separate knowledge bases exist for each of the three types of liner materials. An example of some of the rules used for HDPE is given in Figure 2. The total number of rules for all materials is 347.

All of the inferencing that takes place with the rule base is carried out using Prolog's built-in backwards chaining mechanism. Calls are made to C functions to carry out such procedural tasks as entering raw immersion test data, fitting trend lines to the data, and displaying and printing reports of the system's findings. Figure 3 shows an abridged set of hypothetical immersion test data fed into FLEX and a portion of the resulting output.

FLEX's performance was tested by comparing its recommendations against those of five liner specialists on 14 different

sets of immersion test data. The one expert who provided the most input into FLEX showed perfect agreement with its conclusions on all 14 data sets. The other specialists were asked to review only those data sets for the liner material they were most familiar with. In these cases agreement only ranged between 33 and 50 percent. However in all disagreements, FLEX always took a conservative stance by questioning the chemical resistance of the liner where the specialist did not. FLEX's performance continues to be informally reviewed by a knowledgeable HWERL staff member for immersion test data received from regional offices on a periodic basis.

7. Development Issues

From its experience in developing FLEX and other expert systems during the last four years, HWERL has recognized a number of important issues that affect the successful implementation of this technology within an organization.

Project Management Experience. One factor contributing to the long development time for FLEX was the fact that it was HWERL's first venture into expert systems. A learning curve had to be climbed by the organization with respect to managing projects in this new area of computer technology. Based on its experience with FLEX and its other systems, the laboratory is much more capable now in defining project requirements and scheduling development tasks for expert systems related work than when it first started.

Availability of Experts. Another factor influencing FLEX's development was the limited availability of recognized liner experts. There were so few of these within the country that essentially all of them were used to either develop or evaluate the system. This created scheduling and logistical problems because they were situated at different locations. It was important to interview them at their home sites so that they had access to their records of past immersion test data. In addition, as might be expected, there were disagreements among the experts at times. Resolution of these situations caused additional delays, especially since it was not practical (or even advisable) to have the experts work out their differences face to face. Although there are no pat solutions to these kinds of problems, expert system project managers should be aware of their potential existence when planning and scheduling development activities.

Software/Hardware Availability. The nature of this issue has changed since 1984 when work on FLEX first began. At that time microcomputer-based shells (i.e., development tools for expert systems) were just coming on the market and were very expensive. Development software was also either not available or not economically viable for the EPA's cadre of mainframe (IBM 3090) and mini- (VAX 785 under VMS) computers. HWERL was reluctant to make large investments in hardware and software for both system

development and implementation without first knowing how expert system technology would be received throughout the Agency. Today the situation is somewhat reversed. The expert system developer can be overwhelmed by the large choice of software products available on a variety of hardware platforms. HWERL is continuing to develop its systems within a microcomputer environment, using both commercial software tools and the Prolog programming language.

Review and Acceptance Procedures. The degree of review and confirmation an expert system must receive prior to its release for general use should somehow be related to the nature of the problem it is tackling and the audience it is intended for. More stringent testing and confirmation procedures are needed for systems that have a greater potential for damage caused from incorrect advice. Likewise, as control over the use of a system decreases, such as through its widespread distribution outside of the developers' organization, the need for tighter quality assurance also increases. Within a regulatory agency such as EPA another issue arises; the creation of an expert system could be considered a de facto method of rule making or guidance development that circumvents the usual formal procedures established within the organization for handling such matters. In the case of FLEX, the client office (Office of Solid Waste and Emergency Response) demanded that the system receive special review and acceptance testing before it could endorse its use in the field. Although this issue has been resolved for FLEX it continues to be a potential problem for other expert systems that involve implementation or interpretation of regulatory policy.

Organizational Priorities. Expert system developers must try to be aware of the impacts that shifts in organizational priorities might have on their activities. Within EPA this typically means changes in regulatory policies and budgets. Systems with projected development times of more than two years are particularly susceptible to being affected. Careful pre-project planning, including close communication with the intended user community to establish their particular sense of priorities, can help minimize the impacts. Fast-tracking the development of an expert system to catch the crest of the wave of its beneficial use may not always be feasible. The nature of these systems is such that doubling the development staff will not produce anywhere near a halving of the development time. One example of an HWERL expert system affected by changes in regulatory policies was the DIKE system created to assist in checking the structural safety of surface impoundments. The applicability of this system has been severely limited because of the virtual halt in construction of new surface impoundments for hazardous wastes due to stricter regulatory requirements and a greater perception of liability risks on the part of owner/operators.

Management Approaches to Development. Traditionally, most large scale computer software development in EPA has followed some form of the Life Cycle Management (LCM) process. With LCM each phase

of the product's development is well planned in advanced and fully documented. In contrast, most expert systems projects follow an iterative pattern of development whereby successive prototypes are tested, evaluated, and then modified or expanded accordingly until the final system requirements are met. Ideally one would like to apply some combination of these approaches to developing expert systems, one that would maintain the accountability and control built into the LCM method yet provide the freedom and flexibility achieved through the iterative prototyping approach. EPA's Office of Information Resources Management is struggling with this issue in its attempt to develop Agency-wide guidelines for managing expert systems development.

8. Conclusions

The last four years have been a period of introduction and experimentation with expert systems in environmental engineering. They have provided valuable experience in learning the limits of the technology, identifying the types of problems for which it is best suited, and learning how to manage system development. They have made the technology accessible to a growing segment of the environmental engineering profession by demonstrating their ease of creation using readily available microcomputer software. However ease of creation should not be equated with successful implementation. In fact it appears that the obstacles to achieving actual use of expert systems in routine engineering practice are perhaps greater than for other types of software. A larger number of successful applications to real engineering problems is needed to fulfill the potential promise of this intriguing technology.

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Table 1. Environmental Legislation Administered by the
U.S. Environmental Protection Agency

Name of Act	Major Provisions
Clean Air Act	Sets air quality standards and source performance standards
Clean Water Act	Sets receiving water quality criteria; Issues permits to waste dischargers; Awards construction grants for treatment facilities
Safe Drinking Water Act	Sets drinking water criteria
Resource Conservation and Recovery Act (RCRA)	Defines and tracks fate of hazardous wastes; Issues permits to waste management facilities; Regulates underground storage tanks
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	Creates a "Superfund" for financing cleanups of abandoned waste sites; manages cleanup operations
Toxic Substances Act	Regulates production, distribution, and use of chemicals

Table 2. Expert Systems Being Developed Within EPA

System	Purpose	Office
Water Permits System	Writes NPDES permits for wastewater dischargers	OW ^a
Cost of Remedial Action System	Estimates national cost of Superfund cleanups	OSWER ^b
QUAL2E Advisor	Recommends parameter values for QUAL2E water quality model	ERL ^c
CORMIX1	Suggests model to use for mixing zone analysis in water quality studies	ERL
Geophysics System	Advises on applicability of geophysical monitoring techniques at waste sites	EMSL ^d
Lab Performance Evaluation System	Assesses quality of analytical work done by EPA contract labs	EMSL
Waste Management Facility Siting Advisor	Evaluates facility siting decisions in or near wetlands	EMSL
Flexible Liner Evaluation Expert (FLEX)	Evaluates chemical resistance of synthetic liners to wastes	HWERL ^e
Dike Stability System (DIKE)	Evaluates structural safety of surface impoundments	HWERL
Waste Analysis Plan Review Aid (WAPRA)	Checks compatibility of waste streams and adequacy of sampling methods at RCRA facilities	HWERL
Closure Evaluation System (EXP-CES)	Evaluates plans to close hazardous waste management facilities	HWERL
Remedial Action Technology Screening (TECHSCRN)	Determines feasibility of various cleanup technologies at hazardous waste sites	HWERL

^aOffice of Water, Washington, DC

^bOffice of Solid Waste and Emergency Response, Washington, DC

^cEnvironmental Research Laboratory, Athens, GA

^dEnvironmental Monitoring Systems Laboratory, Las Vegas, NV

^eHazardous Waste Engineering Research Laboratory, Cincinnati, OH

Table 3. History of FLEX's Development

- =====
- 1984-85: Proof-of-concept system developed for PVC using one expert and in-house knowledge engineer.
- 1985-86: Contractor performs knowledge acquisition for PVC and HDPE using six experts; prototype system programmed on a Symbolics workstation.
- 1986-87: Contractor adds knowledge base for CSPE; system re-programmed in Prolog on a microcomputer using LOTUS 1-2-3 as an interface for data management.
- 1987-88: Validation study made using 14 data sets and five experts; LOTUS 1-2-3 interface replaced with customized interface written in C.
- =====

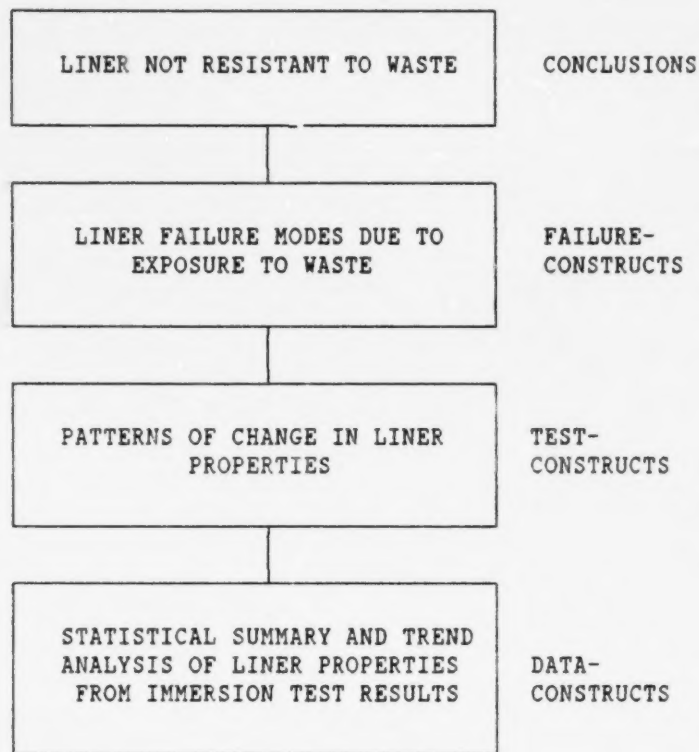


Figure 1. Logic Flow Diagram of FLEX

IF	chemical reaction is indicated
OR	excessive sorption of waste is indicated
OR	excessive softening of the liner is indicated
THEN	the liner is not resistant.

IF	final weight decrease is between 1 and 3%
AND	final tensile strength at yield drops more than 5%
AND	final tensile strength at break drops more than 10%
THEN	chemical reaction is indicated.

IF	final weight decrease is between 1 and 3%
AND	final tensile strength at break drops more than 10%
AND	final elongation at break drops more than 10%
THEN	chemical reaction is indicated.

Figure 2. Sample Rules for HDPE Liners in FLEX

HYPOTHETICAL IMMERSION TEST DATA FOR A HDPE LINER

Property	Average Percent Change in Property			
	1 Month	2 Months	3 Months	4 Months
Weight	-4	-3	-5	-2
Tensile Strength	-7	-14	-10	-17
Modulus	-20	-45	-80	-88

FLEX CONCLUSIONS FOR THIS DATA

The liner is fundamentally inappropriate for the application.

The immersion test results indicate that the liner is not chemically resistant to the waste/leachate.

The immersion test results indicate that the liner material is excessively softened by the waste/leachate. Excessive softening is a sign of poor chemical resistance. A liner material that softens excessively may not be able to withstand the stresses of the waste site and may fail due to tearing or puncture.

Excessive softening of the liner material is evidenced by an excessive loss in its modulus of elasticity. At a lower modulus a given force will produce a greater elongation of the material. Excessive losses in modulus suggest the potential for easier tear, puncture, and break of the liner.

Figure 3. Sample Consultation with FLEX